Case Study in Automation Design Practices:

Analysis of Human-Computer Interaction in Response to FMS Error Messages

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NASA Human Factors Symposium
10/04

Acknowledgements

- NASA Human Automation Design Methods and Tools (HADMAT) Project Element of Airspace Systems
- Rose Ashford (Level 3 Program Manager)
- Michael Feary (NASA - TPC)
- Kevin Jordan (SJSU Foundation)
- Immanuel Barshi (NASA)
- Kevin O'Neill (SWA)
- Randy Mumaw/Dan Boorman (Boeing)

Background of R&D

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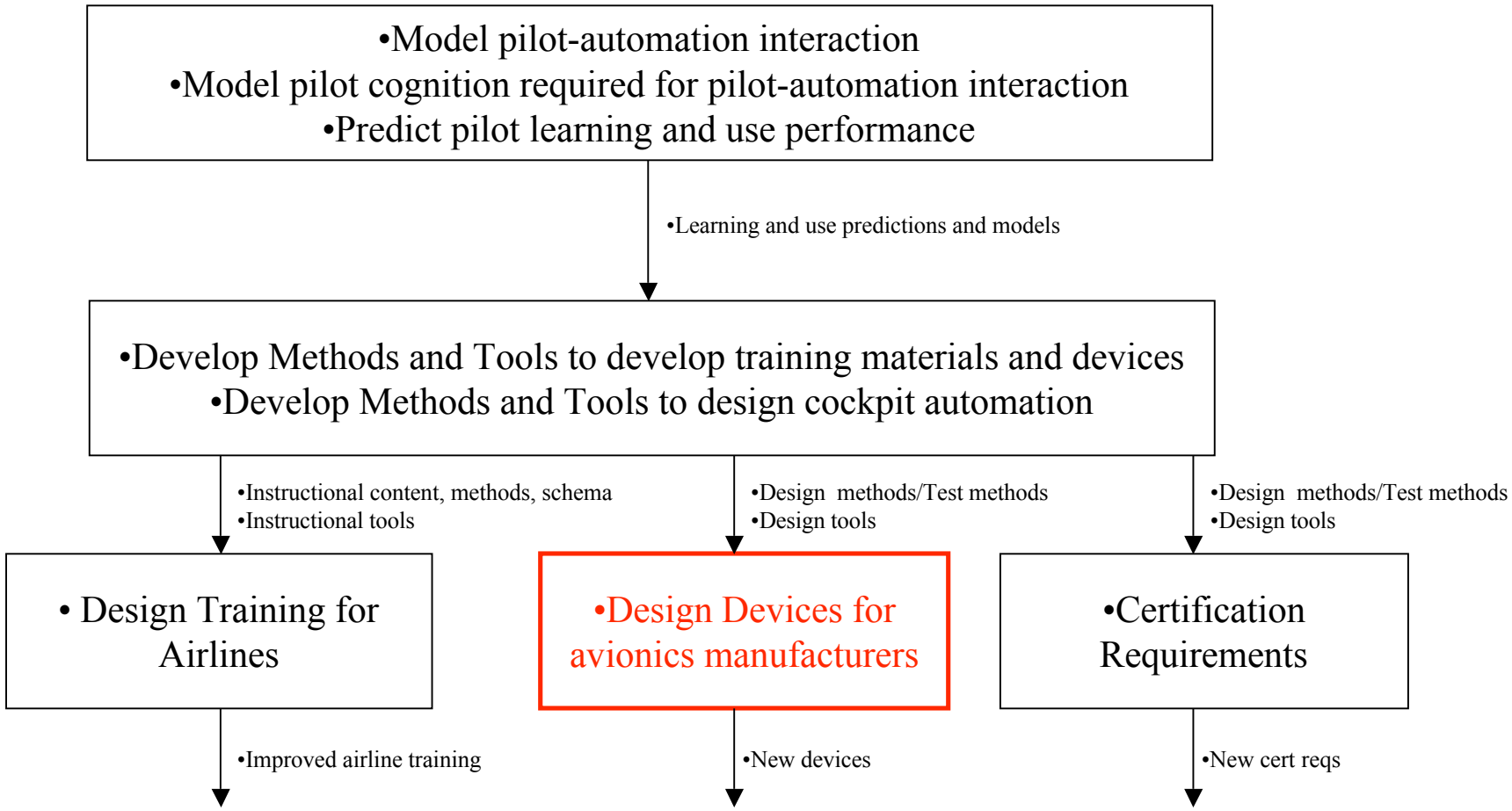
- Traditional design practices fail to match "impedance" between automation & operation (Billings, 1997)
  - HCI of modern systems is left to chance
- Goal of R&D to introduce HCI practices into *mainstream engineering processes* conducted by *software/system engineers*
  - HCI not inspected in by HF expert
- Process Interventions:
  - Task Design Document (TDD)
    - Specification of HCI for all tasks
    - Signed-off by Program Manager
  - Identify and Train 1st principles to engineers
    - Abstracted/simplified models
    - 1st principles, not checklists
    - HC Interaction (not properties of GUI)

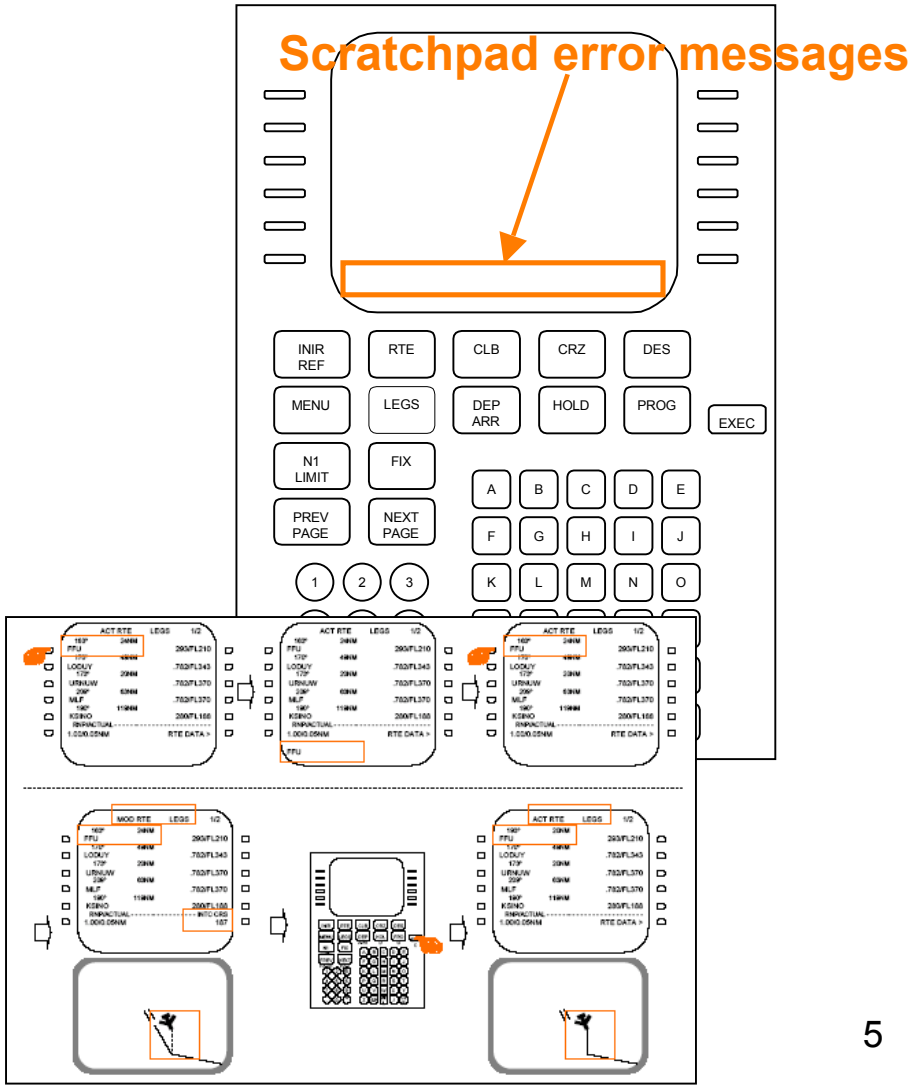
Background of R&D



Case Study in Design Practices

Automation

- Flight Management System (FMS)
- Functions to support approx 101 airline mission tasks:
  - ATC instructions (navigation)
  - Checklist items
  - SOP's (flows) (progress, optimization)
- FMS Error Messages
  - 67 messages
    - Invalid entry
    - System failure
    - Sensor failure
    - Fail reasonableness check
    - Configuration mismatch



Background of Case Study

- Operational Experience
  - Despite benefits, the MCDU/FMS is hard to learn and difficult to use
    - Mumaw, et. al. 2000; BASI, 1999; Air Transport Association 1997, 1998, 1999; Feary et.al. 1998; FAA Human Factors Team 1996
  - Difficulties using the FMS have been attributed to:
    - awkward layout of the MCDU keyboard (Sarter & Woods, 1994)
    - excessive number of pages and features (Billings, 1997)
    - inefficiencies in inputting data (Abbott, 1997)
    - over-reliance on memorized action sequences (Sherry et. al. 2001, 2004)
  - Difficulties using FMS due to absence of feedback (Mumaw, 2000)
      - Aircraft/System state (Wiener's 3 questions)
      - Anomalies (Error messages, Cautions, Warnings) (Boorman, 2001)
  - Responding to FMS scratchpad error messages is a specific problem
    - Jump seat observation of revenue service operations
    - observations of airline training
  - Appearance of message results in question
    - "what does this mean?"
    - "what do we do about it?"

Background of Case Study

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- Costs of Learning FMS
  - Airline pilots invest significant personal time, effort, and energy into developing skills to become proficient using FMS
    - Need to pass Proficiency Checks, Line Checks
    - 35 – 50 hours of their own time (Polson, Irving, Irving)
  - Airlines invest significant resources into training
    - developing skills to proficiency in pilots
    - 3-5 weeks transition/new hire
      - 3 days + sim time for FMS

Case Study in Design Practices

Design Process

- Quality, safety ensured by regulations
  - FARs lead to TSO and STC
    - Not based on 1st principles
    - Lessons learned from accidents/incidents
    - Absent on usability and training (time/cost) issues
    - Address workload at very high level
  - Engineering Process (DO-178B) lead to Software Certfication
    - Best practices
    - Emphasis documentation, traceability, review/testing
    - "System is certified when paperwork exceeds Takeoff Gross Weight of Aircraft"
- FARs not integrated into process
- Software certification (and therefore Design Engineers) evaluated on process only
- Many HCI design issues solved by software engineers

- **Need 1st principles to make sure FARs/Issues accounted for by software engineers in the process**

Background of Case Study

- For scratchpad error messages:
  - Why were these issues not addressed during the “DO 178B-like” design process ?
  - What can we do about this ?
- Traditional HF not working in the “DO 178B-like” design process
  1. Many GUI design decisions made by software engineers deep in the process
  2. Spiral design and Change Request processes constantly spawn changes
  3. One small change has large HCI implications
  4. HF inspections are too little, too late
  5. Checklists for GUI properties do not address HCI interaction (i.e. formulation of Tasks)
- **Need 1st principles that software engineers can apply**

Organization of Presentation

1. Method of HCI Analysis
   - How engineer can look at HCI
2. Results & 1st Principles of Design
   - What existing systems look like
3. Design Interventions
   - What to do about it
4. Conclusion

Method

- Use B777 FMS as representative sample
  - 67 error messages

- 4 Part Analysis
  1. Estimate **Frequency** of Event that Prompts Message
  2. Estimate **Severity** of Event that Prompts Message
  3. Define **HCI** in Response to Event/Message
  4. Classify **Type of Cognition** for Response (See/Remember)

Method

1. Estimate **Frequency** of occurrence of each Event/Message
   - Very Infrequent
     - occurs once in every 101+ flights
   - Infrequent
     - occurs once in every 21 - 100 flights
   - Occasional
     - occurs once in every 5 – 20 flights
   - All
     - occurs once in every 1-4 flights

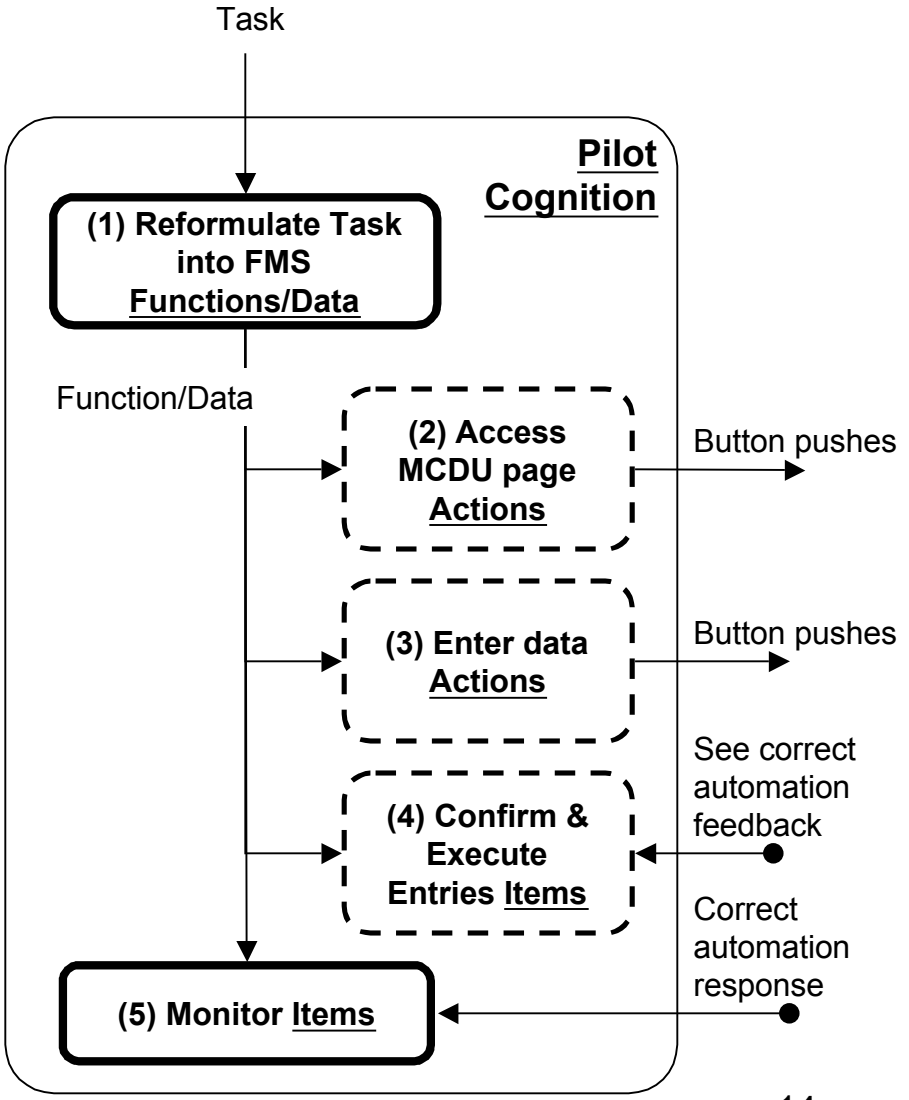
Method

Step 2) Estimate **Severity** of each Event/Message

- Severe
  - flight cannot continue
  - requires immediate attention
- Major
  - Long-term flight outcome in jeopardy
  - requires immediate attention/except for other critical tasks
- Minor
  - no impact
  - address time permits

Method

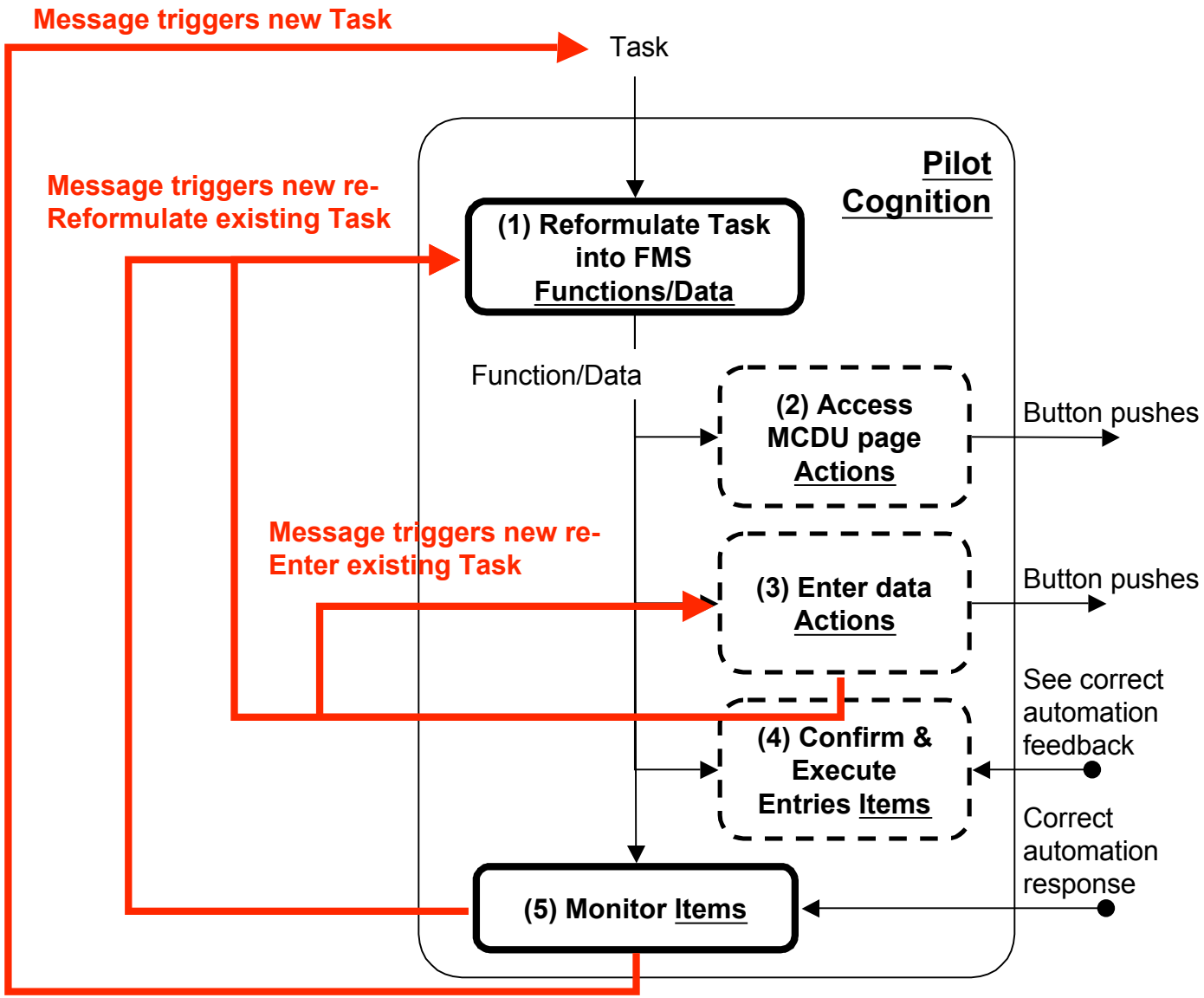
3. Define **HCI** in response to message
   - 5 stage model of Human-Computer Interaction
     1. Identify **F**unction/Data
     2. **A**ccess Page
     3. **E**nter Data (format, range, …etc)
     4. **C**onfirm & Execute
     5. **M**onitor



Method

3) Define **HCI** in response to message
   - Identify step in F-A-E-C-M in which message occurs
     - Message occurs following pilot Entry stage
       - Message may have context, less ambiguous
     - Message occurs during Monitor stage
       - Message has no context/ambiguous
   - Identify steps in F-A-E-C-M model in response to message
     - Message triggers pilot to start a *new* **Task** (1)
     - Message triggers pilot to **re-Reformulate** *current* Task (1)
     - Message triggers pilot to **re-Enter** for *current* Task (3)
     - Message triggers pilot to pilot to **Monitor** *current* Task (5)

Method


Message triggers new Task
Task
Pilot Cognition
Message triggers new re-Reformulate existing Task
(1) Reformulate Task into FMS Functions/Data
Function/Data
(2) Access MCDU page Actions
Button pushes
Message triggers new re-Enter existing Task
(3) Enter data Actions
Button pushes
See correct automation feedback
(4) Confirm & Execute Entries Items
Correct automation response
(5) Monitor Items

Method

4) Classify **Type of Cognition** for Response (See/Remember)

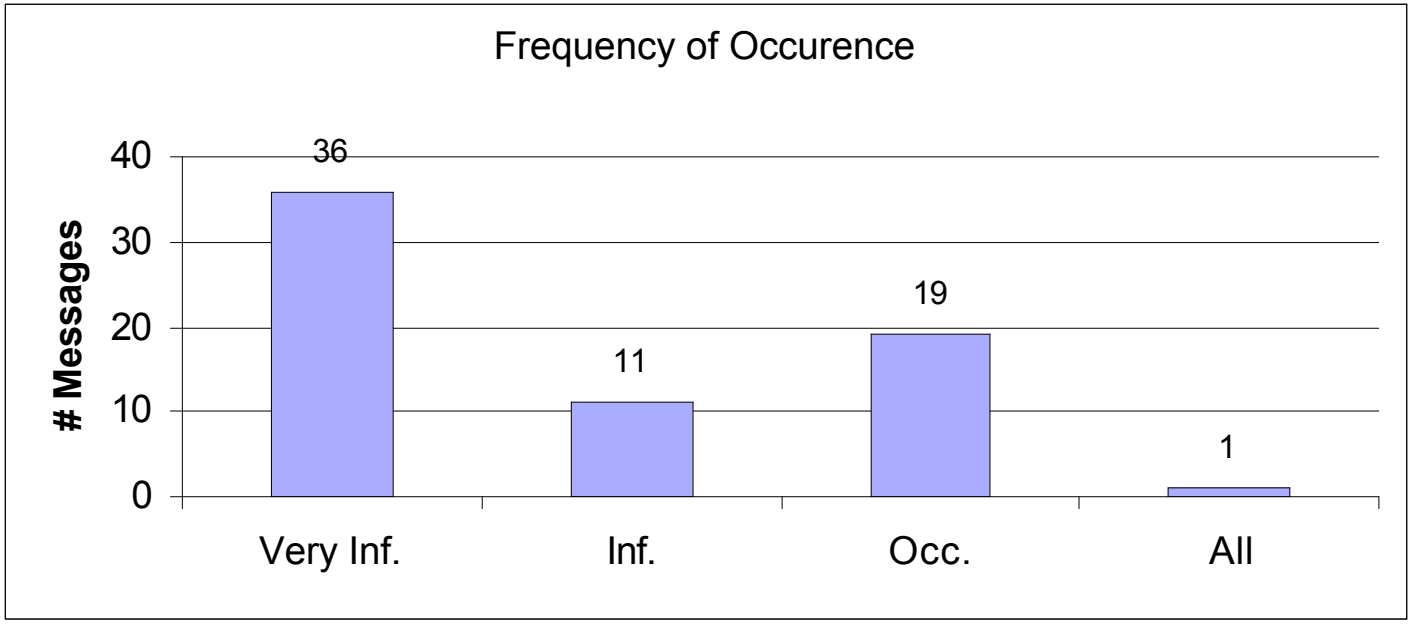
- <u>See/Remember Analysis</u>
  - ***See*** response occurs when Message provides pilot with visual cues to guide next actions
  - ***Remember*** response occurs when Message requires pilot to remember next actions
- Study limited to initial response to message (not whole action sequence)

- See/Remember is design heuristic for practicing software engineers
  - Not adequate theoretical explanation for underlying pilot cognition
  - Designed explicitly as 1st principle for software engineers

Results

- B777 – representative FMS
- 67 messages analyzed (FMS Pilots Guide)
  - Result in 70 tasks
- Team
  - Airline pilot instructor (16 years)
  - Senior Cognitive Scientist (40 years)
  - Human Factors Researcher with Multi-engine rating (10 years)
  - Avionics designer (20 years)
- Analysis to criteria
- Consensus required

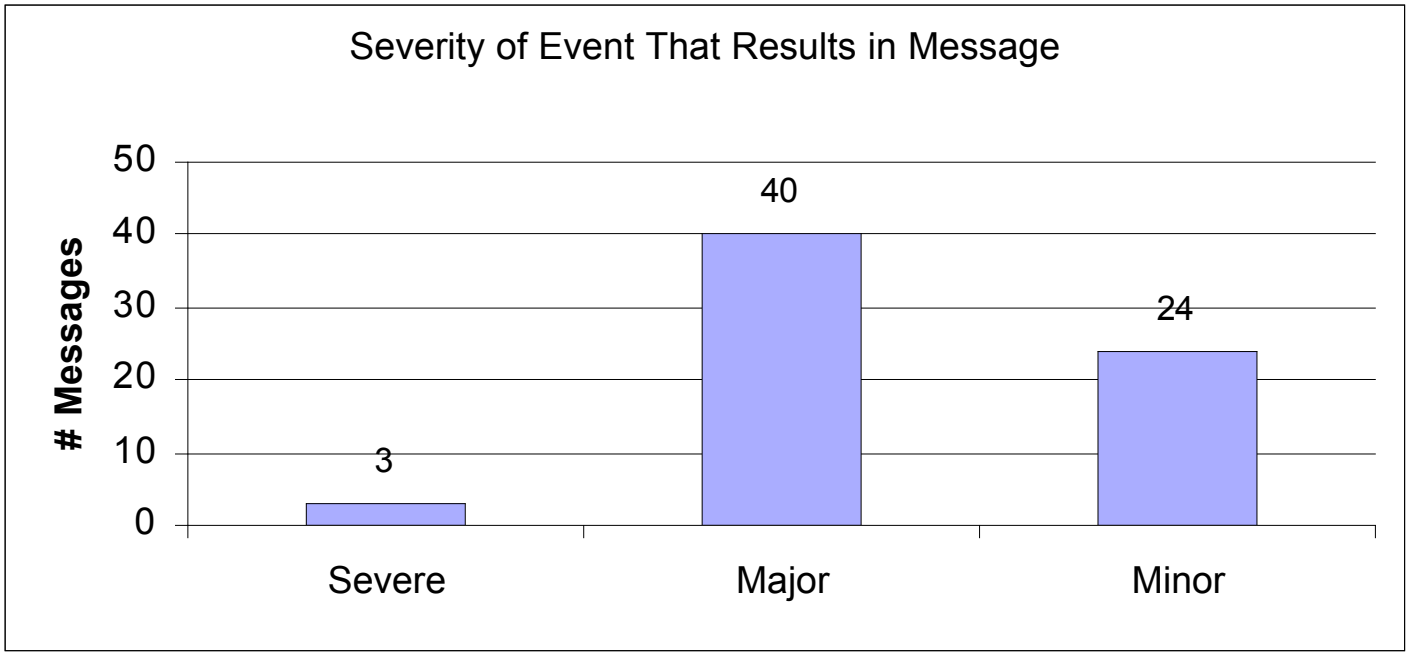
Results (1) – Frequency



- **54% Very Infrequent (< 100 flights)**
  - CHECK AIRLINE POLICY
- 16% Infrequent (20 – 100 flights)
  - GPS/INERTIAL NAV ONLY
- 28% Occasional (5 – 20 flights)
  - RESET MCP ALT
- <1% All the time
  - TAKEOFF SPEEDS DELETED

Design Implications:
Very low frequency leads to forgetting correct interpretations and actions

Results (2) - Severity



- **Severe (< 1%)** – flight cannot proceed
  - FUEL DISAGREE – PROG 2/2
- **Major (60%)** – attend immediately
  - INSUFFICIENT FUEL
- Minor (40%) – attend time permitting
  - CRS REVERSAL AT FA FIX

Design Implications:

Severity demands rapid, reliable response (no time for reflection)

Results (1&2) - Frequency * Severity

Frequency Event / Severity	Very Infrequent	Infrequent	Occasional	All
Severe	**2**	1	-	-
Major	**24**	9	5	1
Minor	9	1	13	-

- 38% Severe/Major AND Very Infrequent
  - VERIFY POSITION
  - THRUST REQUIRED
  - RW/ILS CRS ERROR

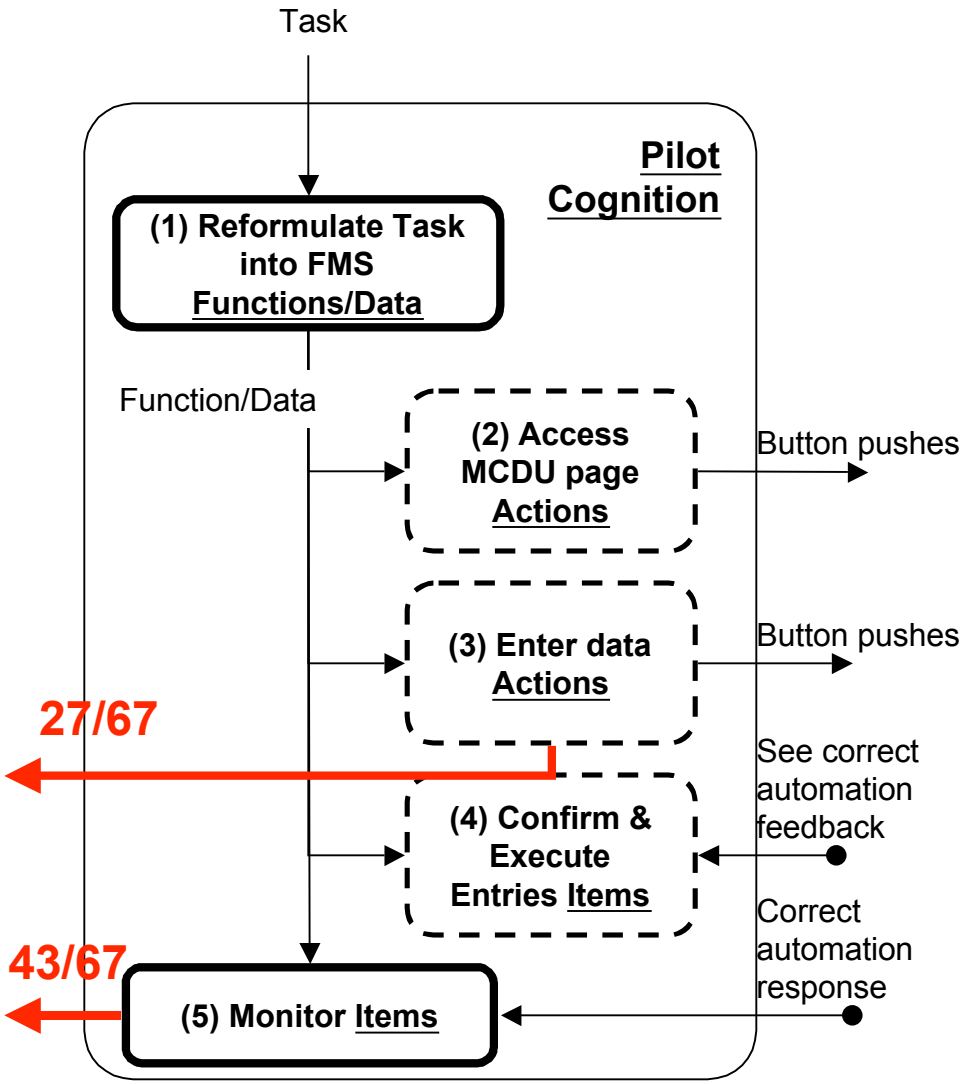
Design Implications:

•Humans respond poorly to unexpected events in time critical environments

Results (3) – Response to Message

- Message occurs while:
  - Entering data (40%)
    - NOT IN DATABASE
    - ROUTE FULL
    - ILS TUNE INHIBITTED – MCP
  - Monitoring (60%)
    - INSUFFICIENT FUEL
    - RWY/ILS FREQ ERROR
    - THRUST REQUIRED

Design Implications:
Entry: Context of message leads to ease in response
Monitoring: Ambiguity in context causes difficulty in response

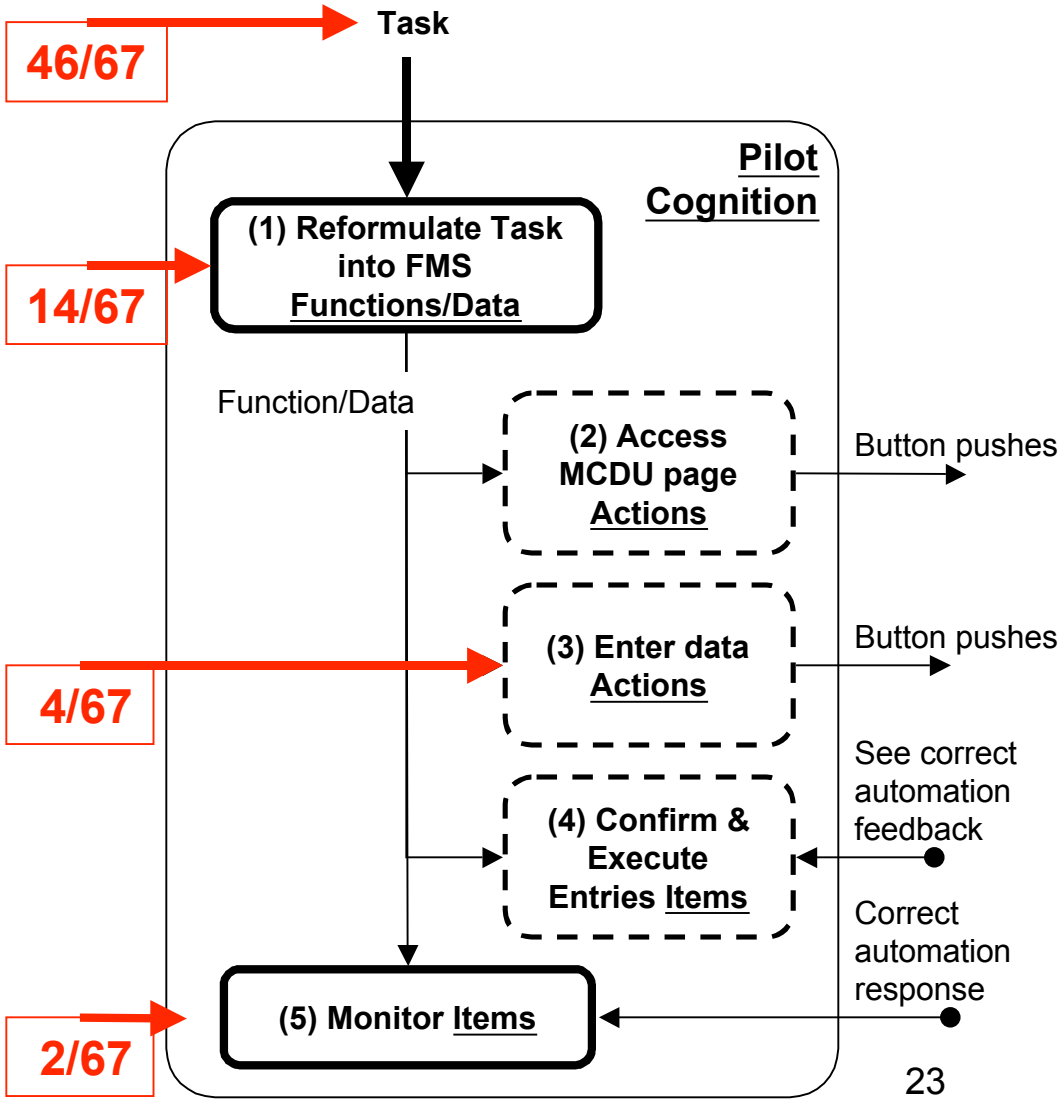


Results (3) – Response to Message

- Message results in:
  - New Task (69%)
    - INSUFFICIENT FUEL
    - RESET MCP ALT
    - RWY/ILS CRS ERROR
  - Re-Reformulate (21%)
    - MAX ALT XXX
  - Re-enter (6%)
    - INVALID ENTRY
  - Monitor (2%)
    - ROUTE X UPLINK LOADING

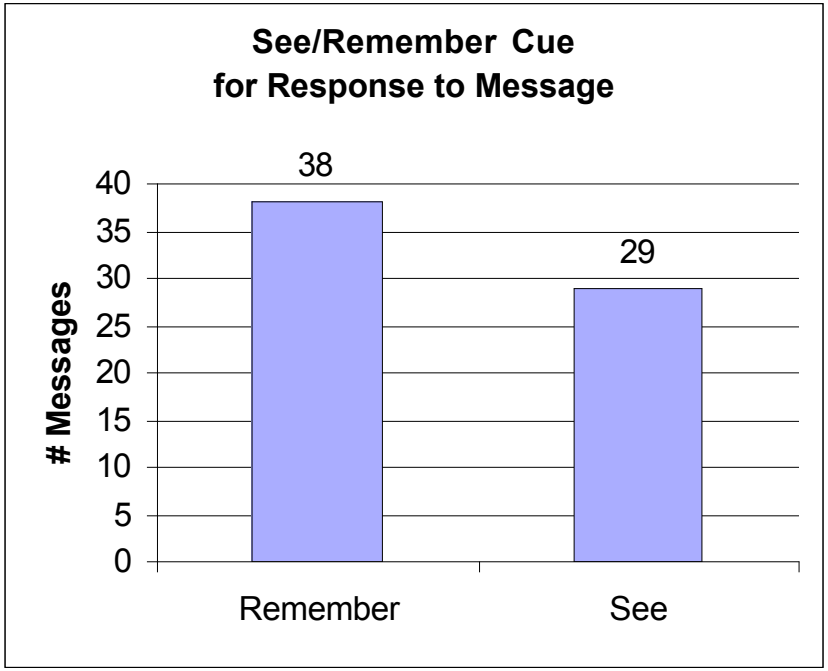
Design Implications:

- Messages create new tasks (not just feedback on last action)



Results (4) – See/Remember

- **57% messages** – Pilot must **Remember** next F-A-E-C-M action
  - CHECK AIRLINE POLICY
    - Remember this means Call Maintenance
  - FUEL DISAGREE – PROG 2/2
    - Remember this means do Fuel Checklist
  - INSUFFICIENT FUEL
    - Remember this could be the result of several factors: WINDS, LEGS, ROUTE
    - Remember the underlying model used by FMS to compute Fuel at Destination
- 43% messages – Pilot can **See** next F-A-E-C-M action
  - RESET MCP ALT
  - CHECK ALT TGT
  - DRAG REQUIRED



Design Implications:

- See is more reliable than Remember
- See less workload than Remember
- See is faster to learn than Remember
- See ensures competence longer than Remember

Results (4) – See/Remember

- Two "styles" of message
  - **Information message** (59/67)
    - Identify situation/context
    - No guidance for response (Pilot must See or Remember)
    - 23 – following Enter – some context
      - INERTIAL/ORGIN DISAGREE
      - LIMIT ALT XXXX
    - 36 – during Monitor
      - END OF ROUTE
      - INSUFFICIENT FUEL
  - **Task message** (9/67)
    - Identify task
    - 2 – following Enter
      - ENTER INERTIAL POSITION
    - 7 – during Monitor
      - NAV INVALID – TUNE XXX

Design Implications:

- Task message requires Reformulation only
- Information message requires Comprehension, then Reformulation

Design Interventions

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- First Principles for HCI Design by Software Engineers
  - Frequent tasks
    - Pilots will Remember action sequences due to frequent use independent of presence of visual cues
    - Pilots will learn faster with visual cues (See)
  - Infrequent tasks
    - Pilots will only remember action sequences with visual cues (See)
    - Pilots will learn faster with visual cues (See)
  - Tasks composed of F-A-E-C-M stages
    - Pilot action (cognitive or physical) must be designed for each stage

Design Interventions

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- Task Design Document (TDD)
  - Part of DO-178B and DO-278 software design process
- TDD includes:
  - List of airline mission tasks
  - Frequency of tasks
  - Severity of tasks
  - F-A-E-C-M steps for each task
  - See/Remember for each step
- Program Manager signs-off on TDD
  - May need waiver for too many Remember steps

Design Interventions

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- Message characteristics:
  - Infrequent occurrence
    - Pilots will not be exposed to build competence through repetition
  - Severe/Major consequences
    - Pilots will have to respond rapidly, reliably
- Desired Message properties:
  - Provide visual cues for F-A-E-C-M action sequence

Design Interventions

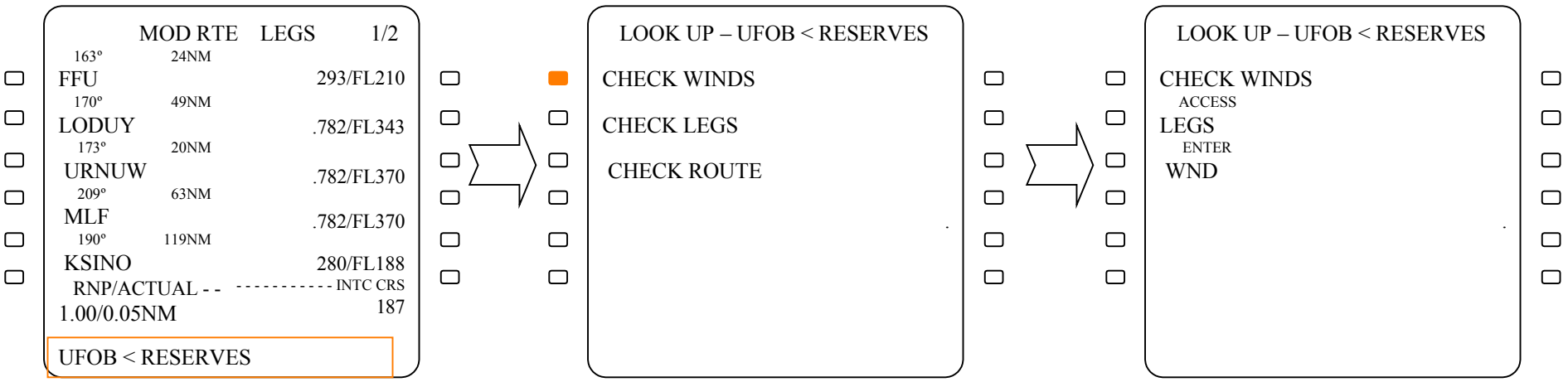
- Components of message:
  1. Situation/Context description
  2. Task description
  3. Next action guidance
  - <Situation> - <Task>, <Next Action>
- Contents of description
  - Use terms of MCDU/FMS
    - INSUFFICIENT FUEL → UFOB AT DEST < RESERVES
    - Page titles
    - Field labels

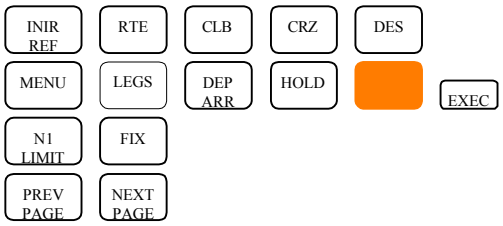
Design Interventions

Current Message	Proposed Message
INSUFFICIENT FUEL	UFOB AT DEST < RESERVES – CHECK WINDS/LEGS/RTE
INERTIAL/ORIGIN DISAGREE	INERTIAL/ORIGIN POS DISAGREE – RE-ENTER ORIGIN, START RE-ALIGNMENT

Design of Interventions

- On-demand Look-up/Training





Conclusions

- Design of messages **cannot** be left to chance
- Cognition required to perform each task must be analyzed
  - 1st principles: F-A-E-C-M & See/Remember
- Same issues apply to graphical user interfaces

- Task Design Document (TDD)
  - part of approved certification design process (DO-178B)
- NASA toolset/analysis available (Feary and others)

- Future Work:
  - FAA Certification (DO-178B, 278B)
  - Aircraft Manufacturers/Avionics Designers
  - Transfer technology to Healthcare, transportation
  - Airline training, Airline training equipment manufacturers